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DOI: https://doi.org/10.1093/mnras/stt1990

Originally published at:
Bonoli, S; Mayer, L; Callegari, S (2014). Massive black hole seeds born via direct gas collapse in galaxy mergers: their properties, statistics and environment. Monthly Notices of the Royal Astronomical Society, 437(2):1576-1592.
DOI: https://doi.org/10.1093/mnras/stt1990

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **437,** 1576–1592 (2014) doi:10.1093/mnras/stt1990
Advance Access publication 2013 November 14

Massive black hole seeds born via direct gas collapse in galaxy mergers: their properties, statistics and environment

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Accepted 2013 October 15. Received 2013 October 15; in original form 2012 November 14

ABSTRACT

We study the statistics and cosmic evolution of massive black hole seeds formed during major mergers of gas-rich late-type galaxies. Generalizing the results of the hydrosimulations from Mayer et al., we envision a scenario in which a supermassive star can form at the centre of galaxies that just experienced a major merger owing to a multiscale powerful gas inflow, provided that such galaxies live in haloes with masses above 10^{11} M$_\odot$, are gas rich and disc dominated, and do not already host a massive black hole. We assume that the ultimate collapse of the supermassive star leads to the rapid formation of a black hole of 10^5 M$_\odot$ following a quasi-star stage. Using a model for galaxy formation applied to the outputs of the Millennium Simulation, we show that the conditions required for this massive black hole formation route to take place in the concordance Λ cold dark matter model are actually common at high redshift and can be realized even at low redshift. Most major mergers above $z \sim 4$ in haloes with mass $>10^{11}$ M$_\odot$ can lead to the formation of a massive seed and, at $z \sim 2$, the fraction of favourable mergers decreases to about half. Interestingly, we find that even in the local universe a fraction (∼20 per cent) of major mergers in massive haloes still satisfies the conditions for our massive black hole formation route. Those late events take place in galaxies with a markedly low clustering amplitude, that have lived in isolation for most of their life and that are experiencing a major merger for the first time. We predict that massive black hole seeds from galaxy mergers can dominate the massive end of the mass function at high ($z > 4$) and intermediate ($z \sim 2$) redshifts relative to lighter seeds formed at higher redshift, for example, by the collapse of Pop III stars. Finally, a fraction of these massive seeds could lie, soon after formation, above the $M_{\rm BH}-M_{\rm Bulge}$ relation.

Key words: black hole physics – galaxies: active – galaxies: formation – quasars: supermassive black holes – cosmology: theory.

1 INTRODUCTION

Accreting black holes of masses $>10^8$ M$_\odot$ are the only known astrophysical objects able to produce the enormous amount of energy released by active galactic nuclei (AGN; Lynden-Bell 1969), and the brightest of these objects, *quasars*, are seen at redshifts as high as ∼7 (Mortlock et al. 2011). The existence of supermassive black holes (black holes with mass $>10^6$ M$_\odot$) at the centre of nearby non-active galaxies has been also confirmed in the last few decades thanks to the observation of the gravitational influence of these objects on the surrounding gas and stars (e.g. Kormendy 2004).

While the existence of black holes in the cores of most massive galaxies is now well established, and a lot is now known about their evolution and relation with the host galaxies across cosmic time (e.g. the reviews of Ho 2010; Kormendy & Ho 2013), the origin of these objects is still largely uncertain: several channels of black hole formation have been envisioned and explored, but when and where the progenitors (‘seeds’) of these massive black holes formed is still a topic of intense theoretical investigation (see the recent reviews by Volonteri & Bellovary 2012; Haiman 2013). According to the ‘Pop III’ scenario, black holes are the descendant of Population III stars, the first generation of stars formed from pristine gas in dark matter (DM) haloes of $\sim 10^6$ M$_\odot$ (e.g. Bond, Arnett & Carr 1984; Haiman & Hui 2001; Madau & Rees 2001); these remnant black holes would have masses of few tens or few hundreds of solar

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masses, although recent numerical simulations have shown that the protostellar disc of Pop III stars could fragment, lowering the initial mass function of the stars and, consequently, of their remnant black holes (Clark et al. 2011; Greif et al. 2011). To grow in a short time to one billion solar masses (the mass estimated for the black holes powering the quasars seen at $z \sim 6$), the Pop III remnants would have to have formed at $z \gtrsim 20$ and accrete gas almost continuously at a rate close to the Eddington limit (e.g. Volonteri & Rees 2006; Tanaka & Haiman 2009; Tanaka, Perna & Haiman 2012). Black holes could also be the result of the runaway collapse of nuclear star clusters, but even in this case the black hole starting mass would not be higher than $\sim 10^3\,\mathrm{M}_{\odot}$ (e.g. Portegies Zwart & McMillan 2002; Rasio, Freitag & Gürkan 2004; Devecchi & Volonteri 2009).

To relax the tight constraints on growth rates and formation times required to build up the very massive black holes powering high-z quasars, the 'direct collapse' scenario has become more and more attractive, as the starting black hole mass could be few orders of magnitude higher (10^4–$10^6\,\mathrm{M}_{\odot}$). Such massive black hole seeds originate from dense clouds of gas (Rees 1984) at the centre of galaxies (or protogalaxies) and likely collapse into a 'supermassive' star; the supermassive star would then either entirely collapse into a black hole before reaching equilibrium if not supported by rotation (e.g. Hoyle & Fowler 1963; Baumgarte & Shapiro 1999; Shibata & Shapiro 2002; Montero, Janka & Müller 2012) or form a massive black hole via a 'quasi-star' (Begelman, Rossi & Armitage 2008; Begelman 2010). In the direct collapse scenario, the most difficult step is to get a massive and dense enough central gas cloud, as the gas has to lose its initial angular momentum and reach the galactic centre before cooling and fragmentation are able to trigger star formation. Most works in the literature have focused on the formation of black holes from direct collapse in isolated metal-free protogalaxies (e.g. Lodato & Natarajan 2006, 2007; Wise, Turk & Abel 2008; Regan & Haehnelt 2009; Johnson et al. 2011), as even small traces of metals can shorten the gas cooling time significantly (Omukai, Schneider & Haiman 2008). Even in a metal-free environment, though, molecular hydrogen cooling has also to be prevented, which may be possible thanks to fluctuations in the Lyman–Werner background (Dijkstra et al. 2008; Agarwal et al. 2012). One could relax the assumption of a metal-free environment if the gas inflow rate to the centre is higher than the star formation rate, that is, if enough gas can be brought to the centre before the bulk of star formation takes place (Shlosman, Frank & Begelman 1989; Begelman & Shlosman 2009). Series of subsequent gravitational instabilities which can lead to accretion rates of 1–10 $\mathrm{M}_{\odot}$ at sub-parsec scales have indeed been seen in the evolution of gas-rich and disc-dominated galaxies in the multiscale nested simulations by Hopkins & Quataert (2010).

Mayer et al. (2010, hereafter M10) have recently shown that even higher central inflow rates are possible in gas-rich major mergers of galaxies without a pre-existing central massive black hole. Using a set of numerical simulations with extremely high spatial resolution (0.1 pc), M10 found that mergers can produce a gravoturbulent disc in the nuclear region of the remnant galaxy. The disc is stable against fragmentation, but features a strong spiral pattern which supports efficient inflow of gas towards the galactic centre. This strong inflow produces a central rotating cloud of $\sim 10^8\,\mathrm{M}_{\odot}$ and of the size of few parsecs, which soon becomes Jeans unstable and collapses to sub-parsec scales. The central gas inflow rate is similarly high even in simulations in which gas cools efficiently and leads to rapid star formation of several thousand $\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ in the nuclear region (see online supplementary information in M10). The inflow rates from the nuclear disc are so strong that this occurs in only about 10^5 yr. The resolution of the simulation did not allow Mayer et al. to investigate further the fate of the nuclear cloud, but the cloud is seen to be Jeans unstable down to the smallest resolved scales. This collapsing cloud is thus a likely precursor of a supermassive star. Soon after formation, the core of rotating supermassive stars is likely to collapse into a black hole of $\sim 100\,\mathrm{M}_{\odot}$, as the time-scale of nuclear burning is very short ($\sim$1 Myr). In the 'quasi-star' picture (Begelman et al. 2008; Begelman 2010), as the central black hole starts accreting, the surrounding gas is inflated into a pressure-supported envelope. While the envelope loses mass through winds, the black hole keeps accreting at super-Eddington rates, as the Eddington limit is imposed on the much larger mass of the envelope, and not on the mass of the black hole itself. Dotan, Rossi & Shaviv (2011) estimated that black holes in this configuration can quickly grow to 10^4–$10^5\,\mathrm{M}_{\odot}$, provided that their surrounding envelopes are above $\sim 10^7\,\mathrm{M}_{\odot}$, as they would be massive enough for their evaporation time-scale to be longer than the accretion time-scale of the black hole.

Inspired by the numerical results of M10 and the idea of massive black hole seeds forming from the collapse of nuclear clouds via a supermassive star, in the present work we construct an analytical model for the formation of massive seeds in galaxy mergers to be incorporated in a galaxy formation model applied to the outputs of the Millennium Simulation. Our aim is to study whether the conditions for the formation of a massive seed can actually be met in our Universe, what would be the contribution of black holes from massive seeds to the total black hole population and whether the descendants of massive seeds could be observationally recognized. Volonteri & Begelman (2010) made a first attempt to study the cosmological evolution of massive seeds from quasi-stars, linking their formation to the mergers of gas-rich DM haloes and the spin of the haloes, using the observational properties of the black hole population to bracket the values of their model parameters. In the present work, we instead directly use the results of the M10 hydrosimulations to construct a model for the formation of massive seeds where the values of free parameters are suggested by the hydrosimulations themselves, and the resulting predictions are analysed in comparison with available data.

In Section 2, we describe in further details the simulations of M10 and how we generalize their results to create the analytic model used in the galaxy formation simulations. Section 3 contains the results of the paper, which we summarize and discuss in Section 4.

2 MODEL

In this section, we first describe the general properties of the galaxy formation formalism upon which we construct the model for the formation and evolution of black hole seeds (Section 2.1). We then discuss the details of our modelling, the origin of the population of 'light' black hole seeds (Section 2.2) and the details of the hydrosimulations of M10 that inspired our model for the formation of the 'massive' seed population, as finally described at the end of Section 2.3.

2.1 The model of galaxy formation

In the last couple of decades, semi-analytical models of galaxy formation have been extensively exploited to study the basic physical processes that drive galaxy evolution by comparing the global properties of simulated galaxies with observational data (e.g. Kauffmann, White & Guiderdoni 1993; Somerville & Primack 1999; Bower et al. 2006). Indeed, semi-analytical models offer a simple approach to study large samples of galaxies, whose formation and evolution are described by a set of coupled differential equations that combine baryonic physics with the properties of DM halo assembly histories constructed from the extended Press–Schechter formalism or from *N*-body cosmological simulations.

The model used in this work uses the DM merger trees extracted from the outputs of the Millennium Simulation (Springel et al. 2005), an *N*-body simulation which follows the evolution of cosmic structures in a $500^3\,h^{-3}\,\mathrm{Mpc}^3$ volume using $2160^3 \simeq 10^{10}$ DM particles of mass $\sim 8.6 \times 10^8\,h^{-1}\,\mathrm{M}_\odot$. The initial conditions of the Millennium Simulation are based on the cosmological parameters of the *Wilkinson Microwave Anisotropy Probe* 1 (*WMAP*1) and 2dFGRS 'concordance' Λ cold dark matter (ΛCDM) framework,[1] with $\Omega_\mathrm{m} = 0.25$, $\Omega_\Lambda = 0.75$, $\sigma_8 = 0.9$, Hubble parameter $h = H_0/100\ \mathrm{km\,s^{-1}\,Mpc^{-1}} = 0.73$ and primordial spectral index $n = 1$ (Spergel et al. 2003). DM haloes and the embedded subhaloes are identified from the output of the simulation with a friends-of-friends group finder and an extended version of the SUBFIND algorithm (Springel et al. 2001), respectively. DM haloes are considered to be resolved when their mass is above $\sim 10^{10}\,h^{-1}\,\mathrm{M}_\odot$, equivalent to 20 simulation particles. The galaxy formation model follows the merger history of DM haloes and, when a new halo rises above the resolution limit, it gets populated by baryons in the form of hot gas (according to the cosmic baryon fraction), which will start cooling and forming stars according to the analytical prescriptions adopted. We refer the reader to Croton et al. (2006) and De Lucia & Blaizot (2007) for all the details on the prescriptions for gas cooling, star formation, supernova feedback and the other physical processes that shape galaxies and their morphology across cosmic times, and for a description of the model success in reproducing many properties of the observed galaxy population. Here, we modify only the assumptions for the formation and evolution of supermassive black holes.

We consider two different black hole seed formation scenarios. The first one assumes that seeds originate from relatively light seeds, either from massive Population III stars or from the runaway collapse of a nuclear star cluster. This scenario has been already adopted in a number of published works on the coevolution of galaxies and black holes and on the clustering of quasars that are based on the same model of galaxy formation used in this paper (Marulli et al. 2008; Bonoli et al. 2009). The second channel of black hole seed formation that we introduce in this work is based on the results of M10 presented above and aims at describing the formation of massive seeds in major mergers of gas-rich galaxies.

2.2 Light black hole seeds

We assume that every newly resolved galaxy in the simulation contains a black hole descendant of black hole seeds from Pop III stars or the runaway collapse of nuclear star clusters, which likely formed in protogalaxies at $z > 10$ (e.g. Madau & Rees 2001; Devecchi et al. 2010). Given the limited mass resolution of the Millennium Simulation, we cannot directly track the formation and early evolution of these objects in our galaxy formation model, so we have to make some assumptions on the mass of these 'light' seed descendants. Marulli et al. (2008) and Bonoli et al. (2009) had assumed a fixed mass for these black holes as the global properties of black holes and quasars at moderate and low redshift ($z \lesssim 5$), as simulated by our galaxy formation model, are essentially insensitive to the

[1] Guo et al. (2013) showed that there are little differences in the galaxy properties when a *WMAP*7 cosmology is assumed.

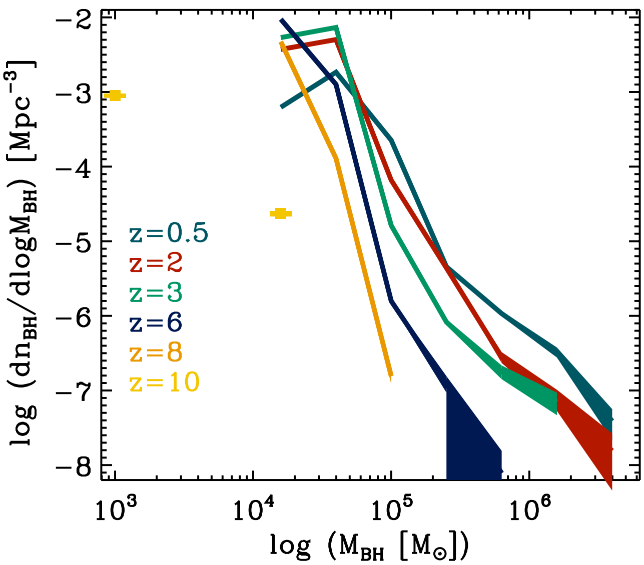

Figure 1. Mass function of the initial black holes, descending from light seeds, that populate newly formed galaxies. Each curve corresponds to a different redshift of formation of the host galaxy, as indicated by the legend. Note that at $z = 10$, the initial black holes can only take the values between 10^3 and $10^4\,\mathrm{M}_\odot$.

mass assigned to black holes in newly formed galaxies, since any subsequent exponential growth washes out traces of the starting mass. However, as we will discuss in detail below, our new model for the formation of massive seeds in galaxy merger requires an accurate census of the mass of black holes, descendant of light seeds, at any time. For this work, we then decided to assume that the mass of the descendant of *light seeds* in newly formed galaxies depends on the mass of the newly resolved halo they reside in and on the redshift at which the halo is resolved. We use the results of a higher resolution simulation, the Millennium-II,[2] to construct a 'library' of typical black hole masses, as a function of the halo mass and redshift. Thanks to the much higher mass resolution of the Millennium-II, mergers of galaxies residing in subhaloes down to few times $10^8\,h^{-1}\,\mathrm{M}_\odot$ are properly followed. Guo et al. (2011) have generated a galaxy catalogue for this simulation, with black holes forming and growing during galaxy mergers as in Croton et al. (2006), and we use this catalogue[3] to generate our 'library'. To compensate for still limited resolution of the Millennium-II, we impose a minimum mass of $10^3\,\mathrm{M}_\odot$ for these light black hole seed descendants (but we note that the results presented in this paper are insensitive to the exact value of the minimum black hole mass imposed). In Fig. 1, we show, at various redshifts, the mass function of the black holes populating newly resolved galaxies, which are assumed to be the descendants of light seeds. At $z = 10$, the typical assigned masses are between 10^3 and $10^4\,\mathrm{M}_\odot$. As redshift decreases, the mass assigned to new black holes is higher and, for galaxies resolved at $z < 3$, it can even be higher than $10^6\,\mathrm{M}_\odot$.

These black holes will keep growing mainly during galaxy mergers. When a merger takes place, we assume that the black holes hosted by the two galaxies coalesce instantaneously (so that each

[2] The Millennium-II is an *N*-body simulation with the same particle number and cosmology of the Millennium, but 125 times better mass resolution since run in a volume of $100^3\,h^{-3}\,\mathrm{Mpc}^3$.

[3] From the online data base http://www.mpa-garching.mpg.de/Millennium/ (Lemson & Virgo Consortium 2006).

galaxy hosts only one black hole at a time), and the resulting black hole starts accreting a fraction $\Delta M_{\rm BH}$ of the surrounding cold gas $m_{\rm cold}$ which depends on the mass ratio of the merging galaxies ($m_{\rm sat}/m_{\rm central}$) and the redshift of the merger (as in Croton 2006). Specifically, the amount of gas accreted by a black hole during a galaxy merger is given by

$$\Delta M_{\rm BH,merger} = \frac{f'_{\rm BH}\, m_{\rm cold}}{1 + (280\,{\rm km\,s^{-1}}/V_{\rm vir})^2}(1 + z_{\rm merg}), \qquad (1)$$

where $m_{\rm cold}$ is the total mass of cold gas in the final galaxy and $f'_{\rm BH} = f_{\rm BH}\ (m_{\rm sat}/m_{\rm central})$ and $f_{\rm BH} \approx 0.02$ is a normalization parameter chosen to match the observed local $M_{\rm BH}-M_{\rm Bulge}$. We note that not all active nuclei show evidence of a recent major merger (e.g. Schawinski et al. 2010) and other physical processes, such as disc instabilities (Draper & Ballantyne 2012; Fanidakis et al. 2012; Hirschmann et al. 2012) and cold flows (e.g. Di Matteo et al. 2012), might be important for the growth of black holes. However, the simple prescription described above (which includes growth by minor mergers) has been shown to be successful in reproducing not only the $M_{\rm BH}-M_{\rm Bulge}$ relations, but also the black hole mass function at $z = 0$ and other observed properties of black holes, quasars and their environment (Marulli et al. 2008; Bonoli et al. 2009), and the choice of populating newly formed galaxies with the typical black holes found in the Millennium-II does not modify these results.

2.3 Massive black hole seeds

The model we construct for the formation of massive black hole seeds from galaxy mergers is based on the assumptions and results of the hydrosimulations of M10. We thus first describe their results and then how we generalize them to build a model to be used in the galaxy formation framework described above.

2.3.1 The evolution of the nuclear region of merger remnants according to hydrosimulations

M10 have used a set of numerical simulations to study the evolution of the nuclear region of high-redshift major-merger remnants. The initial conditions of such mergers will be used in the analytical model that we develop in this paper. The model galaxies adopted in M10 are disc-dominated galaxies (the bulge-to-disc mass ratio is typical of present-day late-type spirals, i.e. $B/D = 0.2$), with a gas/star fraction in the disc of 20 per cent just before the merger occurs (some gas can be consumed by star formation during the tidal interaction preceding the merger, an effect that will depend on the details of the orbital parameters and internal structure of the merging galaxies). The choice of the gas fraction is conservative since high-z discs can be significantly more gas rich (Genzel et al. 2006). Only equal-mass mergers of galaxies were considered, with a dark host halo mass range between 5×10^{10} and $10^{12}\,{\rm M_\odot}$. At lower mass scales, outflows driven by supernova feedback should dominate the gas dynamics and thermodynamics, preventing central accumulation of gas (Governato et al. 2010). Mergers with mass ratio below 0.3 have been shown to be much less efficient at concentrating gas to the inner few tens of parsecs (Callegari et al. 2009; Guedes et al. 2011), and were therefore not considered in M10 nor they will be in the reference model formulated in this paper.

Thanks to the unprecedented spatial resolution of their experiments (the softening length of the gas in the nucleus is 0.1 pc), M10 find that major mergers of discy and gas-rich galaxies in haloes above $10^{11}\,{\rm M_\odot}$ are responsible for a very strong inflow of gas down to scales of a few parsecs, peaking at $>10^4\,{\rm M_\odot\,yr^{-1}}$. A key point is that those inflow rates are a few orders of magnitude higher than those found in simulations of nearly isolated unstable self-gravitating protogalactic discs ($\sim 10^3$–$10^4\,{\rm M_\odot\,yr^{-1}}$ versus a few tens of solar masses per year; see e.g. Regan & Haehnelt 2009). The reason is that in mergers gas can be shocked and torqued much more effectively, losing most of its angular momentum over a short time-scale. Inflows of gas triggered by gravitational instabilities have been seen in simulations also by Hopkins & Quataert (2010) and more recently by Anglés-Alcázar, Özel & Davé (2013): the authors find that instabilities strongly depend on the gas and disc fraction of the host galaxy, and strong inflows might also be possible in isolated turbulent discs. In the present work, we only conservatively consider as possible sites of massive seed formation the remnants of mergers of disc-dominated galaxies, as mergers trigger even stronger inflows than the ones found in the works of Hopkins & Quataert (2010) and Anglés-Alcázar et al. (2013).

A much higher predicted inflow rate is also a difference with respect to semi-analytical models of seed black hole formation via direct collapse (e.g. Volonteri & Begelman 2010), which consider the conditions at the virial radius of the host galaxy halo. Indeed, in M10 gas flows inwards owing to continuous loss of angular momentum by torques and shocks over a wide range of spatial scales (at small scales the torques are provided by spiral arms in the unstable nuclear disc arising at the centre of the merger remnant). The net inflow rate at the centre thus depends on the integrated effect of all the torques at different scales rather than on the conditions at the global galactic or halo scales. The resulting characteristic velocity of the gas is much higher than the free-fall velocity at the halo virial radius, while the gas mass reservoir is still within a factor of a few of the total amount of gas available in the galaxy even at relatively small scales (i.e. the nuclear disc acquires most of the cold gas mass in the galaxy due to angular momentum loss at large scales). Ultimately, this translates into a much higher mass inflow rate that well exceeds the expectation using the free-fall velocity at the scale of the halo. The latter is given by

$$ {\rm d}M/{\rm d}t = m_{\rm d} {V_{\rm c}}^3/G, \qquad (2)$$

where G is the gravitational constant, $V_{\rm c}$ is the virial circular velocity of the DM halo hosting the galaxy and $m_{\rm d}$ indicates the fraction of mass which is able to collapse in freefall. For $V_{\rm c} \sim 150$–$200\,{\rm km\,s^{-1}}$, which were the typical values of the virial velocities of the haloes simulated by M10, one would obtain ${\rm d}M/{\rm d}t \sim$ few tens of ${\rm M_\odot\,yr^{-1}}$ (assuming $m_{\rm d} = 0.05$–0.1 as in Lodato & Natarajan 2006), which is several orders of magnitude lower than what is found in the sub-pc-scale merger simulations. Likewise, while Volonteri & Begelman (2010) (see also Lodato & Natarajan 2006; Volonteri, Lodato & Natarajan 2008) use a threshold in spin parameter of the halo as a further criterion to decide which haloes would undergo seed formation via direct collapse, we avoid that based on the fact that the angular momentum of the gas likely does not trace that of DM at any scale, and especially at small scales the dynamics of the nuclear disc dominates the evolution of the angular momentum (e.g. Danovich et al. 2012; Dubois et al. 2012).

Shortly after the merger, the central region of the galaxy remnant in M10 is characterized essentially by two components.

(i) A rotating nuclear disc, of the size of about ~80 pc and mass of $\sim 10^9\,{\rm M_\odot}$. It is in this nuclear disc where a very large fraction of the gas initially in the galactic disc has accumulated.

(ii) A pressure-supported rotating cloud of the size of few parsecs, and of mass of $\sim 10^8\,{\rm M_\odot}$. This cloud forms from the rapid inflow of gas from the nuclear disc less than a million years after the merger. Due to this strong inflow from the surrounding disc, the cloud becomes Jeans unstable, and eventually collapses to sub-parsec scales.

Once the cloud shrinks to the resolution limit (0.1 pc), the simulation cannot follow the collapse further; hence, the final stage of the cloud is highly uncertain. Moreover, the simulations of M10 do not consider the multiphase nature of the medium. If and how much fragmentation can occur inside the central object once the multiphase nature of the medium is also captured even below pc scales is certainly one of the main uncertainties of our model. We are beginning to study this with radiative transfer and are about to include post-Newtonian corrections that would be relevant if the collapse proceeds even just a bit further than the end state of M10. For the purpose of this work, we assume that a massive seed via a supermassive star phase is formed. The formation of the seed would occur on time-scales short enough ($<10^7$ yr) that, for the purpose of this work, we consider instantaneous. If the supermassive star could collapse directly into a black hole because of a runaway gravitational collapse, the mass of the seed could be very large, comparable with the mass of the whole cloud. Given that the cloud giving rise to the supermassive star likely has some stabilizing angular momentum, we conservatively consider that the supermassive star evolves into a quasi-star, which eventually leads to a seed black hole of $\sim 10^5\,\mathrm{M_{\odot}}$ [see Begelman (2010) and, for the cases of the large inflow rates considered here, Dotan et al. (2011)]. The circumnuclear disc + quasi-star configuration is the underlying structure that we consider to construct our phenomenological recipe of massive seed formation and growth.

Before we start describing this phenomenological recipe, we note that Ferrara, Haardt & Salvaterra (2013) have recently argued that our merger-driven direct collapse model can hardly occur in conditions expected in circumnuclear discs due to the fact that the cooling time is short enough to lead to rapid fragmentation and star formation rather than to a sustained massive inflow as we found in the simulations with a fixed equation of state presented in M10. They argue that an object with a mass of $100\,\mathrm{M_{\odot}}$ can form at most. While it is certainly true that gas thermodynamics plays a major role in our scenario, calling for the need of more realistic radiation hydrodynamics simulations, as also discussed above, we note that their treatment is not really representative of the conditions of the circumnuclear region arising after gas-rich mergers in the M10 simulations. First of all, as they also note, the relevant cooling time-scale here is not the (optically thin) cooling time-scale rather it is the diffusion time-scale of photons since the circumnuclear disc is highly optically thick. The diffusion time-scale of photons due to electron scattering is found to be about 3000 yr by Ferrara et al. (2013) using parameters similar to those in our disc but assuming a mean density rather than the actual density profile in our disc. Based on that they conclude that the cooling time is shorter than the free-fall time; hence, rapid fragmentation will occur. This, however, is misleading, since (1) the free-fall time-scale is shorter than 3000 yr only outside 10 pc in the discs of M10, and (2) in a differentially rotating disc gas cannot collapse on a time-scale smaller than the orbital time, which in the region prone to fast cooling is of the order of 5×10^4 yr. All these are conservative estimates since the mean density that they use is lower than the actual density within 20 pc in the simulations, which would increase the diffusion time-scale. But even discarding that, their conclusion only applies to the very outer, lower density part of the disc which contains a small fraction of the mass, while most of the mass is within about 10 pc (see fig. 1 of M10), and it applies to a relatively long time-scale, within which most of the gas will have already accumulated to the centre due to the inflow in the simulations of M10. Indeed, M10 have shown that even in the very unfavourable case of efficient optically thin cooling, a central mass concentration larger than $10^8\,\mathrm{M_{\odot}}$ arises in the central pc in less than 10^5 yr despite widespread fragmentation (see supplementary information of M10). This is because when the disc becomes violently unstable and fragments, the inflow continues, although in a different regime of a cold, gravoturbulent gas disc rather than a warm Toomre-stable one (see supplementary information of M10). This points to a major ingredient missing in a semi-analytical approach such as that of Ferrara et al. (2013); gas inflows are possible also in gravitationally unstable discs, giving rise to a turbulent state and efficient removal of angular momentum, as discussed also by Begelman & Shlosman (2009). Nevertheless, simulations with more realistic radiation hydrodynamics, incorporating for example flux-limited diffusion or some other approximation to radiative transfer, are needed to place the model on a firmer basis in the future.

2.3.2 *Massive black hole seeds in the galaxy formation model*

In our new model, we assume that massive black hole seeds form during the major mergers of massive gas-rich late-type galaxies that satisfy specific constraints. Mimicking the initial conditions used in the simulations of M10, the exact conditions for inserting a massive seed are the following.

(i) *A major merger*. For our reference model, we impose a minimum mass ratio $M_{\mathrm{gal,1}}/M_{\mathrm{gal,2}}$ of 0.3, where with M_{gal} we refer to the stellar+cold gas component of the galaxy. As discussed above, this is motivated by simulation results (Callegari et al. 2009; Guedes et al. 2011) which showed that mergers of galaxies with smaller mass ratios are not violent enough to trigger strong gas inflows towards the galaxy centre. While a minimum mass ratio of 0.3 is assumed in our standard scenario, for comparison with other works (e.g. Volonteri & Begelman 2010), we will also show some results obtained assuming a minimum mass ratio of 0.1.

(ii) *A minimum mass of the DM halo of the merger remnant* M_{halo} *of* $10^{11}\,\mathrm{M_{\odot}}$. Where M_{halo} corresponds to the subhalo mass for satellite galaxies and the virial mass for centrals. This threshold in halo mass comes from the results of the M10 simulations, which show, with varying mass of the merging galaxies, that the central collapse does not occur below such a mass scale as a result of increased stability of the nuclear disc. Future analysis of an extended sample of numerical simulations will have to clarify if it is indeed the mass or rather the central density of galaxies, as probed by the maximum circular velocity V_{max}, the fundamental variable governing the mass inflow.

(iii) *A bulge-to-total ratio* B/T *of both merging galaxies of at most* 0.2. The results of M10 clearly show the importance of a disc to sustain the spiral patterns able to feed the nuclear region of the merger remnant (see also Hopkins & Quataert 2010; Anglés-Alcázar et al. 2013). Galaxies with such a low B/T ratio have both very large gas fractions, so they potentially have enough fuel to feed the nuclear region of the merger remnant, and the structure for a proper dynamical response to generate the required multiscale gas inflow as a result of tidal interactions (a dominant bulge tends to stabilize a galactic disc even in the presence of strong tidal perturbations, weakening the gas inflow).

(iv) *The lack of a black hole of mass larger than* $10^6\,\mathrm{M_{\odot}}$. As pointed out by M10, any pre-existing massive black hole fed by the inflowing gas would stabilize the nuclear disc via radiative feedback.

We set $10^6\,M_{\odot}$ as threshold, as the feedback from smaller black holes would likely be too weak to halt the gas inflow and only massive black holes might be able to actually reach the centre remnant, thanks to dynamical friction, in time-scales shorter than the time-scale of gas inflow and formation of the central cloud (Mayer et al. 2007; Chapon, Mayer & Teyssier 2013).

If the above conditions are met, we assume that the merger is able to give rise to the high gas inflow rates that lead to the post-merger configuration found by M10: a nuclear cloud of $10^8\,M_{\odot}$ surrounded and fed by a circumnuclear disc. We assume that the central part of the cloud quickly collapses into a supermassive star which, in a short time-scale, gives rise to a black hole of $\sim 10^5\,M_{\odot}$ via a 'quasi-star' (see the discussion above). As the time-scales for these processes are very short compared to the time resolution of the cosmological simulation, we assume that a massive seed of $10^5\,M_{\odot}$ is formed as soon as the conditions on the merger described above are met.

After being formed, the seed can start accreting the gas still flowing from the circumnuclear disc to the surrounding residual cloud. We assume the circumnuclear disc to be 2/3 of the total mass in cold gas of the remnant galaxy, which is approximately the value found by M10. Such high fractions of gas in the central region of major-merger remnants have also been seen in previous simulations (e.g. Barnes & Hernquist 1996). Further assuming that stars in the disc form with a 30 per cent efficiency (which can be seen as an upper limit on the star formation efficiencies in molecular clouds at small scales, i.e. well below 100 pc; e.g. Evans et al. 2009), about 1/3 of the gas in the nuclear disc can feed the remnant nuclear cloud and then be available for the black hole.

With these numbers in mind, we assume that the remnant of the nuclear cloud and the gas still flowing from the nuclear disc form a 'reservoir' of gas of $M_{\rm r} = 2/9 M_{\rm gas}$ (with $M_{\rm gas}$ being the total cold gas in the galaxy), from which the newly formed massive black hole seed can accrete. The black hole now grows at much lower rates than the super-Eddington rates that made its fast formation possible during the quasi-star phase, and it keeps growing until its feedback energy is able to unbind the reservoir (see the sketch in Fig. 2).

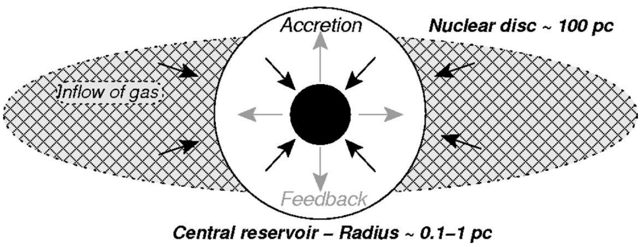

Figure 2. Sketch of the structure surrounding the massive black hole seed (of $\sim 10^5\,M_{\odot}$) formed from the supermassive star after the quasi-star phase. The reservoir of gas from which the black hole grows includes the remnants of the central massive cloud from which the initial supermassive star formed and the gas still flowing from the nuclear disc. The growth of the seed stops once its feedback energy balances the binding energy of the central reservoir.

Equating the total energy emitted by the black hole during the accretion phase and the binding energy of the gas reservoir, we get

$$\int_{t_i}^{t_f} \epsilon_{\rm feed}\epsilon_r \dot{M} c^2 {\rm d}t = \frac{G M_r^2}{r_{\rm r}}, \tag{3}$$

where $\epsilon_{\rm feed}$ is the efficiency of feedback coupling, ϵ_r is the radiative efficiency, $\dot{M}$ is the accretion rate and $r_{\rm r}$ is the radius of the region. In numerical simulations which assumed Bondi-type accretion, the value of $\epsilon_{\rm feed}$ is usually set to be 0.05 (e.g. Di Matteo, Springel & Hernquist 2005); in our simulation we do not have information on the properties of the gas to properly model a Bondi-like growth, but the accretion is spherically symmetric, so we decided to use $\epsilon_{\rm feed} = 0.05$ in our reference model; however, we will also show the properties of massive seeds when assuming $\epsilon_{\rm feed} = 0.01$. The amount of gas accreted by the black hole seeds is then given by

$$\Delta M_{\rm BH,reservoir} = \frac{1}{\epsilon_{\rm feed}\epsilon_r c^2}\frac{G M_r^2}{r_{\rm r}}. \tag{4}$$

We assume that $\Delta M_{\rm BH,reservoir}$ is accreted at the Eddington rate of the black hole.

The model developed here relies on few parameters, whose values are set following the assumptions and results of the hydrosimulation results of M10. The only parameter not well constrained by the simulations is $r_{\rm r}$, the radius of the central reservoir. We decided to assume two values for this parameter, $r_{\rm r} = 1$ and 0.1 pc, which are plausible assumptions in the range of the characteristic sizes of the supermassive clouds found in M10. Given the importance of $r_{\rm r}$ in setting the final mass of massive seeds after their first accretion phase, most of the results in the next sections will be discussed for both values of this parameter. A summary of the parameters that regulate our model for massive seeds is given in Table 1. The reference model is presented for two values of the reservoir cloud, 1 and 0.1 pc (from now called 'reference1' and 'reference01', respectively). In the model 'merger01', we explore how the results change when allowing also mergers down to a 0.1 mass ratio to be the possible sites for massive seed formation. In the model 'feedback01', we set the efficiency of feedback coupling to 0.1 instead of 0.5. As we will see in the next section, changing the reservoir size or changing the efficiency of feedback coupling has consequences on the final mass of the newly formed massive seeds, while a change in the minimum mass ratio has a direct effect on the statistics of direct collapse events. After the formation and having accreted from the reservoir cloud, the massive black hole seeds can further grow when their host galaxy experiences a new merger. In those subsequent accretion events, the massive black hole seeds are treated in the same manner as the descendants of light seeds: they merge with the black hole hosted by the companion galaxy and grow

Table 1. List of the parameters that set the stage for the formation and growth of massive seeds and their values for the different models explored. Only the minimum merger ratio, the efficiency of feedback coupling $\epsilon_{\rm feed}$ and the radius of the reservoir cloud $r_{\rm r}$ (highlighted in bold) are varied, while the other parameters are kept constant.

	$\boldsymbol{M_{1,\rm gal}/M_{2,\rm gal}}$	$M_{\rm halo,min}$	B/T	$M_{\rm BH,min}$	$M_{\rm r}$	$\boldsymbol{\epsilon_{\rm feed}}$	$\boldsymbol{r_{\rm r}}$
reference1	**0.3**	$10^{11}\,M_{\odot}$	0.2	$10^6\,M_{\odot}$	$2/9M_{\rm gas}$	**0.5**	**1 pc**
reference01	**0.3**	$10^{11}\,M_{\odot}$	0.2	$10^6\,M_{\odot}$	$2/9M_{\rm gas}$	**0.5**	**0.1 pc**
merger01	**0.1**	$10^{11}\,M_{\odot}$	0.2	$10^6\,M_{\odot}$	$2/9M_{\rm gas}$	**0.5**	**1 pc**
feedback01	**0.3**	$10^{11}\,M_{\odot}$	0.2	$10^6\,M_{\odot}$	$2/9M_{\rm gas}$	**0.1**	**1 pc**

according to equation (1). We use this prescription for black hole growth for all the mergers that do not satisfy the condition for the creation of a massive seed, as we do not have at the moment enough input from small-scale hydrosimulations to attempt a general new recipe that would hold for all kinds of mergers.

Finally, if a massive seed merges with a light seed, the new black hole will have the 'light' or 'massive' seed tag, depending on which black hole progenitor is larger.

3 RESULTS

After having set the theoretical assumptions that define our model, we now look at how frequently the imposed conditions for the formation of a massive seed are met as galaxies evolve from high redshift to the local universe (Section 3.1). We then look at the relative importance of black holes from massive and light seeds in defining the total black hole population (Section 3.2). Finally, we compare the typical environment in which the descendants of light and massive seeds reside, trying to find differences which could help tracing back the origin of black holes (Section 3.3).

3.1 Statistics of events

We first of all explore if and how frequently the conditions for the formation of a massive seed from galaxy mergers described in Section 2.3.2 are actually met in a realistic ΛCDM universe.

In the top panel of Fig. 3, we show, as a function of redshift, the probability of satisfying each of our conditions for the formation of a massive black hole seed. Of all mergers of galaxies whose

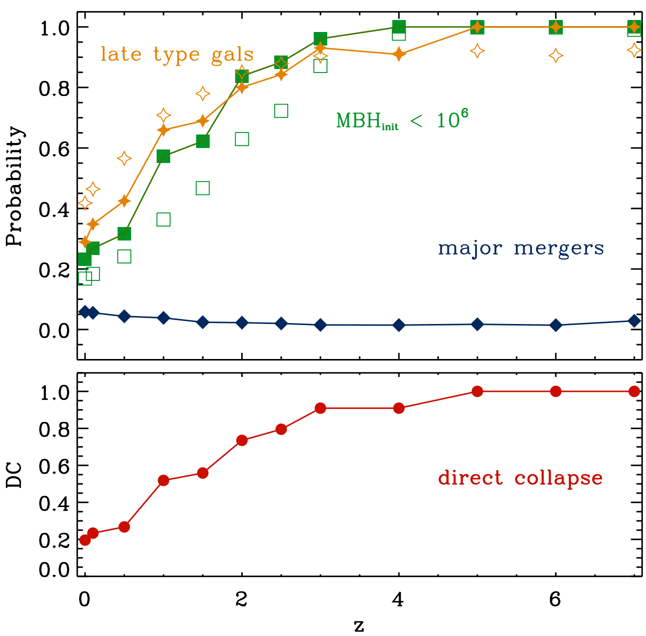

Figure 3. For the merger events of galaxies hosted by haloes of at least 10^{11} M$_{\odot}$, probability of satisfying the conditions imposed for the formation of a massive seed via direct collapse: the blue diamonds show the fraction of major mergers (with 0.3 mass ratio), the green squares show the fraction of merging galaxies with a black hole smaller than 10^5 M$_{\odot}$ and the orange stars indicate the fraction of mergers that involve late-type galaxies. The red bullets in the lower panel indicate the fraction of major mergers that satisfy all the conditions for the formation of a black hole seed from direct collapse. The empty symbols indicate the fraction of galaxies with a small black hole and with late-type morphology for major mergers only.

remnants are hosted by a subhalo of at least 10^{11} M$_{\odot}$, the fraction of major mergers (of mass ratio 0.3) is approximately constant with redshift, and of the order of few per cents (blue diamonds). The fraction of merging galaxies hosting a black hole (descendent of a light seed) smaller than 10^6 M$_{\odot}$ is, as expected, a strong function of redshift (green squares): at high redshift, the probability that a major merger involves galaxies with a small black hole is quite high (and even equal to 1 above $\sim z = 4$), but it decreases sharply at lower redshift and, in the local universe, about 20 per cent of both merging galaxies have a black hole smaller than 10^6 M$_{\odot}$. If the merging galaxies are experiencing their first merger, the mass of the black holes they host is still the mass assigned when the host galaxies were first formed. In this work, the mass assigned to these black holes, assumed to be the descendants of light seeds, is estimated using the outputs of the Millennium-II simulation, as discussed in Section 2.2. If we had assumed a fixed mass of 10^3–10^4 M$_{\odot}$ for the light seeds, as done in previous works, the probability of satisfying the constraint on the pre-existing black hole mass would have been higher, in particular at low z. Moreover, it might be plausible that the descendants of light seeds do not populate all galaxies, as we conservatively assume here, as some Pop III stars might never reach high enough masses to form a black hole (see, e.g., the discussion in Volonteri & Bellovary 2012). In this respect, then, the numbers shown here can then be considered as lower limits. On the other hand, a channel of black hole feeding not considered in the reference model which could make black hole masses rise significantly before any merger takes place is growth by secular instabilities. We tried to add this growth channel to look for any change in the statistics of events of massive seed formation found with our reference model. Our galaxy formation model already has a prescription[4] for testing the instability of galactic disc: we simply assumed that when instability is detected, not only the bulge grows, but also a small fraction of the gas[5] in the galaxy reaches the nuclear region and feeds the central black hole. While we find that the additional growth by disc instability has a detectable effect in increasing the total normalization of the black hole mass function, it does not influence the statistics of massive seed formation. Disc instability events, in fact, mainly take place in galaxies that never satisfy the other conditions for the formation of a massive seed: as discussed by Guo et al. (2013), disc instability is important for building up bulges in Milky Way-type galaxies, which we do not expect to be hosting a massive seed.

The other constraint we impose for the formation of a massive seed is the low bulge-to-disc ratio of the merging galaxies. The probability of having two disc galaxies involved in a merger is shown in the same figure (orange stars). The fraction of merging disc galaxies is also quite high (between 0.8 and 1) above $z = 3$, but decreases with decreasing redshift, as the total fraction of disc galaxies is lower. The morphology in the code is treated as in Croton et al. (2006) and De Lucia & Blaizot (2007); in a later development of the model introduced by Guo et al. (2011), galaxies suffer a more

[4] The stability criterion used in the model is the one introduced by Mo, Mao & White (1998): the stellar disc of a galaxy becomes unstable when this inequality is met: $\frac{V_c}{(Gm_{\rm disc}/r_{\rm disc})^{1/2}} \leq 1$. If the disc is unstable (its mass in stars is larger than the mass that gives rise to the inequality), the excess stellar mass is transferred from the disc to the bulge to restore stability.

[5] We assume here that 6 per cent of the gas can reach the centre, times a scaling with the virial velocity of the halo as in equation (1). This is approximately the value of gas available in a merger of 0.3 ratio (see again equation 1), which we find a sensible enough value for this simple test.

gradual stripping of cold gas when they become satellites, with respect to the previous models. In this case, satellite galaxies have even lower *B/T* ratio at all z, as the gas remains on the satellite and can keep cooling and forming stars in the disc, and central galaxies also have, on average, lower *B/T* disc ratio. With this newer version of the model, the fraction of merging galaxies with low *B/T* ratio would then be even higher, and our estimates on the probability of satisfying the condition on the galaxy morphology can be regarded as lower limits.

The resulting fraction of major mergers that satisfy all the conditions to form a massive seed black hole is shown in the lower panel of the same figure: all major mergers above $z \sim 4$ could potentially lead to the formation of a massive black hole from direct collapse. At $z \sim 2$, the fraction of major mergers that can form a massive seed has decreased to half, and in the local universe only 20 per cent of major mergers lead to direct collapse. Yet, it is particularly interesting that our model predicts the presence of favourable conditions for the formation of black holes from direct collapse in a small fraction of major mergers at lower z and even in the local Universe. Schawinski et al. (2011) have detected a triple-AGN system at $z \sim 1.35$ composed of rapidly growing black holes of estimated masses of 10^6–10^7 $M_\odot$ embedded in clumps. The low masses and the high Eddington ratios suggest the recent formation of these black holes. While there are not yet detected signatures of a recent merger for this system, the possibility that these AGN could be newborn massive black holes formed during a merger is very intriguing, and certainly worth further investigation both on the observational and theoretical side. In Section 3.3, we briefly discuss some properties of the environment of massive seeds formed at recent times.

In Fig. 4, we show the redshift evolution of the number density of major-merger as well as of massive seed formation events. As from our simulation we have information on the *merger rate*, that is, the number of mergers per time interval within two subsequent snapshots, to obtain the number density of possibly visible events, we have to assume a typical time-scale for the duration of the events. The numbers shown in the figure are obtained assuming, for each merger, a visibility time of 10^8 yr, which is approximately the estimated lifetime of bright quasars (e.g. Martini 2004). Following this definition, the number density of major-merger events of galaxies hosted by subhaloes above 10^{11} $M_\odot$ is indicated by the red solid line. The red bullets show the number density of these major mergers that also satisfy all the conditions for the formation of a massive seed: as discussed above, essentially all major mergers at high redshift satisfy the conditions for the formation of a massive seed, while, at lower redshift, fewer major mergers can lead to a new massive seed. To guide the eye with an order-of-magnitude comparison, we plotted in the same figure the number density of high-redshift observed optical quasar reported by Shen et al. (2007). While a direct comparison between the observed quasar properties and our black hole population is beyond the scope of this paper, we see that the number of events possibly forming direct collapse seeds is large enough to account for bright optical quasars. In the same figure, the blue dashed line and the blue triangles show the number density of mergers and events of massive seed formation if the threshold for a major merger is decreased from 0.3 to 0.1 [model 'merger01', as used in Volonteri & Begelman (2010) in their study of the evolution of quasi-stars]. Clearly, the number of events assuming a smaller mass-ratio threshold is much higher, approximately an order of magnitude higher at all redshifts. As discussed in Section 2.3.2, we conservatively use a mass threshold of 0.3 in our reference model as mergers of galaxies with smaller mass ratios might not be violent enough to lead to the high gas inflow rates necessary to form a supermassive cloud. Finally, in Fig. 4 we also show the number density of major-merger and massive seed formation events for our reference model, but assuming a much shorter visibility time (1 Myr), which is approximately the lifetime of the supermassive star and quasi-star phase. We postpone to a future work a detailed study of the observability of individual events of massive seed formation, but this would be approximately the number density of supermassive stars/quasi-stars from galaxy mergers as predicted by our model.

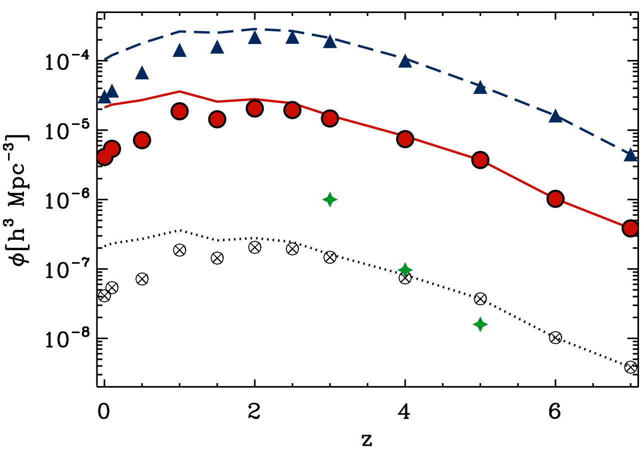

Figure 4. Number density of major mergers (mass ratio >0.3) of galaxies hosted by subhaloes of at least 10^{11} $M_\odot$, obtained from the rate of events and assuming a 'visibility time' of 100 Myr (red solid line). Of these mergers, the number density of the ones that satisfy the requirements for the formation of a massive seed from direct collapse is indicated by the large red bullets. The blue dotted line and the blue triangles show the same quantities, but assuming that the threshold for major mergers is 0.1 instead of 0.3. Finally, the black dashed line and the crossed black circles show again the number densities of major mergers (with 0.3 mass-ratio threshold) and events of massive seed formation, but assuming a 'visibility time' of 1 Myr. The green stars indicate the number density of observed high-redshift quasars from Shen et al. (2007), put here to provide the reader with an order-of-magnitude comparison.

3.2 Black hole properties

We now turn to the global properties of the supermassive black hole descendant of massive seeds, comparing them both with observations and with the properties of black holes with a light seed progenitor.

We start by looking at the evolution of the mass function, for black holes both with light and massive seed progenitors (Fig. 5). We show here the results using the 'reference1' and 'reference01' models, which assume a reservoir of gas of 1 and 0.1 pc, respectively. In the first case (upper panel), the black holes from massive seeds (red curves) dominate almost the entire mass function at $z \sim 6$ and above; at $z = 3$ the mass function is already dominated by light seed descendants (blue curves), except for the most massive end. For a smaller reservoir cloud (0.1 pc, lower panels), the direct collapse black holes can grow to larger masses after their formation: in this case, a substantial number of black holes with masses above 10^8 $M_\odot$ are already present at $z = 6$, and the direct collapse black holes dominate the massive end of the mass function down to $z \sim 1$. For 'reference1', at $z = 0$, the number density of black holes from light seeds is a couple of order of magnitude higher than the number density of black holes formed from direct collapse in a wide mass range. Only at the very massive end (above 10^9 $M_\odot$), direct collapse

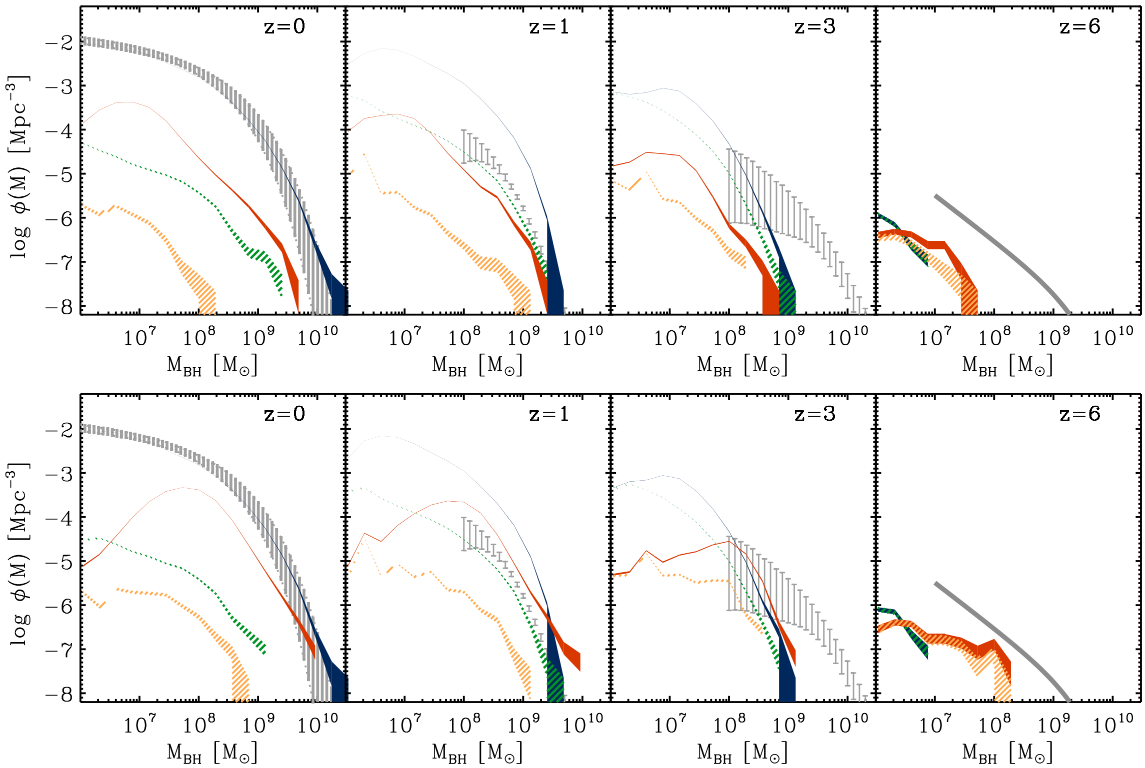

Figure 5. Black hole mass function at various redshifts as indicated in the panels for our reference model. For the top panels, we have assumed that newly formed massive seeds grow from a gas reservoir of 1 pc, while for the bottom panels a radius of 0.1 pc is assumed. The blue curve shows the mass function of black holes with a light progenitor, while the dark red curve shows the mass function of black holes with progenitor from direct collapse. The dashed curves indicate the mass functions of black holes emitting at more than 10 per cent the Eddington limit, for the light seed descendants and massive seed back holes (light green and orange, respectively). The width of the lines includes the $1-\sigma$ error. At $z=0$, the grey band shows the black hole mass function calculated by Shankar et al. (2004), while at $z=1$ and 3, the grey band is the estimate for the mass function derived from broad-line quasars by Kelly & Shen (2013). The grey curve at $z=6$ indicates the BH mass function estimated by Willott et al. (2010b).

black holes are about 10 per cent of the total population. For the case in which the gas reservoir is 0.1 pc, at $z=0$ and above $10^8\ M_{\odot}$, the massive seed descendants are only about one order of magnitude less numerous than the light seed descendants with the same final mass. Around $10^{10}\ M_{\odot}$, the black holes with a massive progenitor are almost as numerous as the light seed descendants.

While a search of the model parameters that better match the observed black hole mass function is beyond the goal of this paper (given also the still large uncertainties in the estimates of the mass function at high z), we show in the same figure some black hole mass functions reported by various authors. At $z=0$, the grey band indicates observational estimates from Shankar et al. (2004): as already reported by Marulli et al. (2008), the match between observations and model predictions is here very good. At higher redshift, we show the mass functions estimated from bright quasars by Kelly & Shen (2013) at $z=1$ and 3 and by Willott et al. (2010b) at $z=6$ (again with grey curves). We qualitatively compare to these results by calculating in our models the mass function of active black holes, defined to be the black holes accreting at a rate higher than 10 per cent of their Eddington rate. The resulting mass functions are shown in the figure by the orange curves (for massive seeds) and green curves (for light seeds). Essentially all black holes with a massive progenitor are actively growing at $z=6$, but the fraction of active black holes strongly drops with decreasing redshift (orange curves). This indicates that the most massive black hole seeds formed and grew at early time. Indeed, the most massive end of the massive seed black hole mass function does not evolve much below $z=3$. On the other hand, the descendants of light seeds are strongly growing at intermediate and low redshifts, and, by $z=0$, they completely dominate the mass function also at the highest masses. This is likely due to the fact that the most massive galaxies (and DM haloes) mainly assembled at late times (De Lucia & Blaizot 2007; Angulo et al. 2012), when the probability of satisfying our constraints for the formation of a massive seed is lower. When compared to the observational data, at $z=1$ the mass function of active black holes is dominated by the light seed remnants (green curves), and the match with observational estimates is quite good. At higher redshifts, the predicted active mass function is lower than observed, both for the light and massive seed remnants, although in the model with a 1 pc reservoir (orange curves in the lower panels) the model predictions get closer to the observational estimates. While strong accretion in massive seeds or more efficient formation of massive seeds (see also Fig. 6) might help populating the massive end of the active mass function at high z, the lack of a large population of actively growing massive black holes at high redshift is indeed currently an issue in our model (as it will also be shown later, when we discuss the predictions for the evolution of the luminosity function). This might be related to a similar underestimate of the galaxy stellar mass function at high z (e.g. Guo et al. 2011), and/or the need of more efficient black hole feeding during mergers or secular processes.

Fig. 6 shows the different evolution of the mass function of massive seed remnants predicted by modifying model parameters: we show, as in the previous figure, the reference model with both a

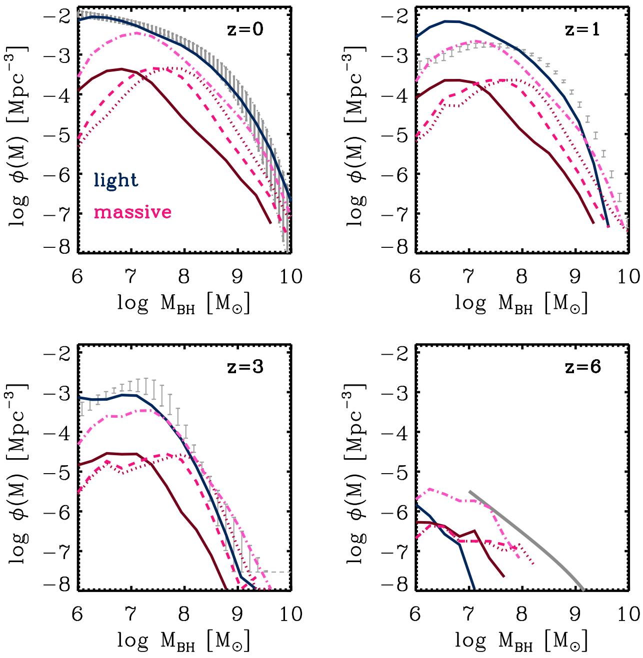

Figure 6. Black hole mass function at various redshifts for various models for the massive seeds: reference model, with reservoir of 1 pc ('reference1', solid line); reference model with 0.1 pc reservoir ('reference01', dotted line); model with efficiency of feedback 0.01 instead of 0.05 ('feedback01', dashed line); model with 0.1 minimum mass-ratio threshold for the mergers that can lead to the formation of massive seeds ('merger01', dot–dashed lines). The blue curve shows the mass function of the light seed remnants, as predicted by the reference model, but very similar in all models. The grey bands show observational results from Shankar et al. (2004) at $z = 0$, from Merloni & Heinz (2008) at $z = 1$ and 3 and from Willott et al. (2010b) at $z = 6$.

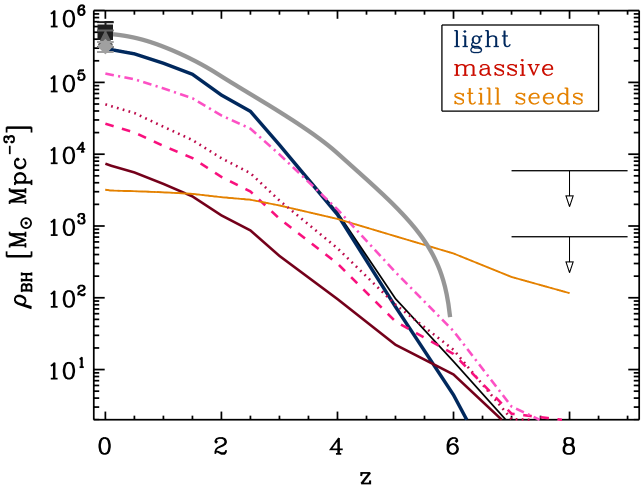

Figure 7. Evolution of the black hole mass density for the various black hole populations. The red curves show the evolution of the mass density for different parameters of the massive seed models, as in Fig. 6. The blue solid line refers to the evolution of the mass density of black holes descending from a light seed; this is plotted only in the case of the reference model for clarity, but the evolution is quantitatively approximately the same for all the models. The solid black line shows the sum of the solid red and blue lines. The orange line shows the evolution of the mass density of black holes that never experienced growth. The points at $z = 0$ are from Yu & Tremaine (2002), Shankar et al. (2004) and Graham & Driver (2007), the thick grey line shows the black hole mass density evolution derived by Shankar, Weinberg & Miralda-Escudé (2013) and the upper limits at $z \sim 8$ are from Treister et al. (2011).

reservoir of 1 and 0.1 pc (solid and dotted red lines), and we also add the models in which we assume the feedback efficiency ϵ_r to be 0.01 instead of 0.05 ('feedback01', dashed red lines) and the model in which the minimum mass ratio of the merging galaxies which could lead to massive seed formation is set to 0.1 instead of 0.3 ('merger01', dot–dashed red lines). Compared with the reference model with a 1 pc reservoir, we get a shift of the mass function to higher masses if we either decrease the size of the reservoir or decrease the efficiency of feedback. Lowering the mass threshold of the merging galaxies increases instead the normalization at all masses, as the number of events is at least an order of magnitude higher than in our reference model (as shown also in Fig. 4): this is consistent with the result of Volonteri & Begelman (2010), who assume a minimum 0.1 merger mass ratio and find that massive seeds can dominate the black hole number density, even when Pop III remnants are included in the calculation. The mass function of light seed remnants is approximately the same for all models of massive seeds, shown here by the blue solid line. At $z = 0$ and 6, we include again the observational estimates from Shankar et al. (2004) and Willott et al. (2010b). Given the increase in the total normalization, a lower mass threshold of merging galaxies could help matching the $z = 6$ data, but also a smaller reservoir or lower feedback efficiencies could help forming more massive black holes from massive seeds at high z. At $z = 1$ and 3, we show the mass functions of Merloni & Heinz (2008), and the total mass functions of massive seed + light seed remnants seem to agree well with those estimates.

In Fig. 7, we show the redshift evolution of the total black hole mass density, for the same models of massive seeds formation. In line with the results of the previous figure, the model which predicts the higher mass density of massive seed remnants is the one that assumes a 0.1 merger ratio for the potential site of massive seed formation (dash–dotted red curve). We compare the results with estimates from Shankar et al. (2013), obtained from the AGN luminosity function through a continuity equation (as first suggested by Soltan 1982), and, at $z \sim 8$, with the upper limits suggested by Treister et al. (2011), who estimated the growth of black holes from deep stacked X-ray observations. We find that the total predicted black hole mass density (black line) reproduces quite well existing observational constraints up to $z \sim 3$. Our total black hole mass density then starts to decrease quite rapidly. Massive seeds dominate the mass density above $z \sim 4{-}5$, depending on the specific model assumed. At all redshifts there is also a large population of light seed remnants that never grew because they had never experienced a merger (we remind the reader that in the current version of the model, efficient black hole accretion is triggered only during galaxy merger events) and this population is dominant at $z > 5$. Other channels other than mergers might be important in triggering the growth of these black holes, thus changing the shape of our predicted mass density at high z. Interestingly, if all galaxies are populated by seed black holes, a population of relic black holes is expected in the local universe (e.g. Rashkov & Madau 2013).

We now turn to the model predictions for the bolometric luminosity function of active black holes. We assume that during each accretion event described by equation (1), the luminosity output of the accreting black holes is described by a high-rate accretion phase followed by a quiescent phase, as first suggested by Hopkins et al. (2005). A detailed description of the implementation of this

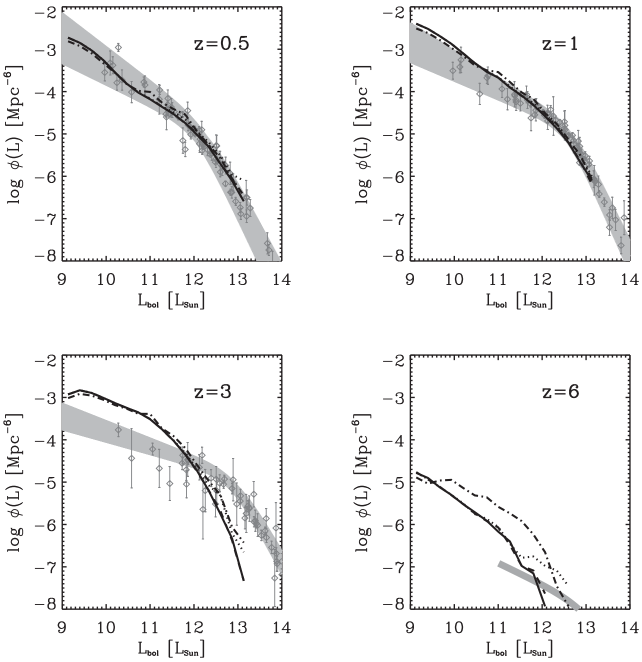

Figure 8. Bolometric luminosity function from accreting black holes (both light and massive seed remnants) at various redshifts. The different black curves refer to differences in the details of massive seed modelling (same line styles as in Fig. 6). The grey bands at $z = 0.5$, 1, 3 are the best-fitting luminosity functions derived by Hopkins et al. (2007) from multiwavelength data indicated by the points. At $z = 6$, the grey curves show the best-fitting luminosity functions of optical quasars derived by Willott et al. (2010a).

light-curve model can be found in Marulli et al. (2008) and Bonoli et al. (2009), with the only difference that we assume that during the rising phase of the light curve black holes accrete at an Eddington rate $f_{\rm Edd}$ randomly extracted from a log-normal distribution peaked at $f_{\rm Edd} = 0.3$, as first suggested by Kollmeier et al. (2006). The luminosity output of newly formed massive seeds is more uncertain: in the model we propose here, most of the growth occurs while still embedded in their gas reservoir, whose properties need to be studied in further details. However, to a first order, we estimate the luminosity output of the newly formed massive seeds assuming that they grow at the Eddington rate and they have a standard radiative efficiency of 0.1. The total bolometric luminosity function of the combined massive and light seed populations is shown in Fig. 8. The various black curves refer to the different models of massive seeds, as considered in Figs 6 and 7. As events of formation of massive seeds decrease with decreasing redshift, the total luminosity function at $z = 3$ and below is dominated by the accretion of light seed remnants, and the different curves become indistinguishable. At $z = 6$, the forming massive seeds are frequent and the predictions depend on the details of the model assumed: as shown in previous figures, the assumption of a threshold mass ratio of 0.1 leads to a much larger number of events, with a consequent increase also in the predicted number density of luminous sources. Assuming a smaller reservoir or a smaller feedback efficiency also help in increasing the normalization of the luminosity function at high redshift.

Our predictions are here compared with the estimate for the AGN bolometric luminosity function suggested by Hopkins, Richards & Hernquist (2007) combining multiwavelength data (grey symbols and grey bands) at $z = 0.5$, 1 and 3. At $z = 6$, we plot the luminosity function of optical quasars from Willott et al. (2010a) (darker grey) and McGreer et al. (2013) (lighter grey): their estimates are in terms of M_{1450}, which we converted to bolometric luminosity with the relation

$$M_i(z = 2) = 90 - 2.5 \log(L_{\rm Bol}), \quad (5)$$

where $L_{\rm Bol}$ is in erg s^{-1} (Shen et al. 2009) and

$$M_{1450} = M_i(z = 2) + 1.486 \quad (6)$$

(Richards et al. 2006). At $z = 0.5$ and 1, the agreement between the model predictions and the observational estimates is quite good. At $z = 3$, we overpredict the number of faint objects and underestimate the number of brightest AGN, as already found and discussed in Marulli et al. (2008) and Bonoli et al. (2009). At $z = 6$, the agreement with observed data is quite good, although the comparison cannot be direct, as our predictions do not account for obscuration.

3.3 Black holes and their environment

Given that we are studying black hole seeds in a full galaxy formation model applied to the outputs of the Millennium Simulation, we have the perfect framework to study not only the cosmological evolution of black holes, but also the large-scale environment in which black holes grow. Once black holes have experienced exponential growth to become the ‘mature’ objects that power AGN, it is impossible to recover information on the properties of their seeds, but the large-scale environment might help us reconstruct the history of the hosted black hole.

3.3.1 Merger histories

We directly compare the merger history of black holes with light and massive seed progenitors. Fig. 9 shows several properties of the merger history of black holes that are descendants of light seeds and direct collapse black holes that had a first accretion phase assuming a reservoir of 1 pc (‘reference1’). All quantities analysed are plotted as a function of the black hole mass at $z = 0$. The top panels indicate the average number of progenitors[6] (or mergers) that contributed to build up the black holes of final mass indicated on the x-axis. Across all masses, light seed descendants and direct collapse black holes seem to have had a similar total number of progenitors (top-left panel). The most massive black holes are sitting in galaxies that had hundreds of progenitors. Of all the mergers, only few of them are classified as major (with mass ratio above 0.3). While there is small evidence that the host galaxies of black holes from massive seeds experience more major mergers than the host galaxies of light seed descendants, the difference is not large, and the overall trend as a function of mass is the same for the two populations (top-right panel). The bottom panels show the average redshifts of the first and last major mergers. We find a clear difference in the median redshift of the first major merger between the most massive light seed descendant and massive seed descendant of the same mass (bottom-left panel): black holes originated from direct collapse are sitting in galaxies that experienced a first major merger at much higher redshifts than the galaxies hosting light seeds (as we have shown in Fig. 3, most major mergers at z above 4 potentially satisfy the conditions we imposed for the formation of a direct collapse

[6] We note that the absolute number of progenitors per galaxy (or black hole) depends on the resolution of the simulation, but the relative difference in the merger history of light and massive seed progenitors is insensitive to the resolution limits.

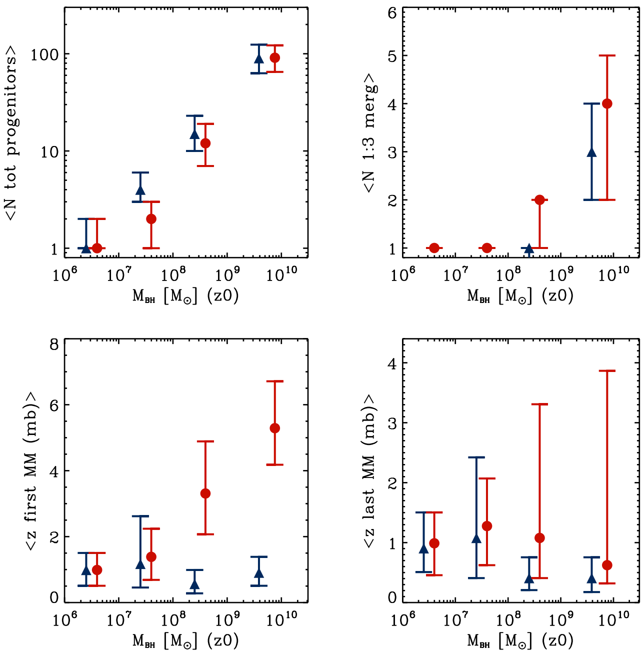

Figure 9. Merger histories of the galaxies hosting light seed descendants (blue triangles) and massive seed black holes in the model with a 1 pc reservoir (red circles), as a function of the black hole mass at $z = 0$. The top-left panel shows the average number of progenitors (mergers), while the average number of major mergers is shown in top-right panel. The bottom panels show the average redshift of the first major merger (bottom left) and the average redshift of the last major merger (bottom right). The error bars bracket the 25th and the 75th percentile range.

black hole seed). As for the typical redshift of the last major merger, galaxies hosting light seeds tend to have the last merger at lower redshift than galaxies hosting massive seeds (bottom-right panel). These differences in merger histories of the galaxies hosting massive and light seed remnants likely affect their morphology, colours and environment, which might thus be important observational signatures for distinguishing the two populations, as further discussed below.

3.3.2 *Scaling relations*

Fig. 10 shows the relation between the black hole and bulge mass at three different redshifts. The white–black area shows the position of the light seed descendants on the $M_{\rm BH}-M_{\rm Bulge}$ plane, where darker pixels indicate a higher number density of objects. The success of the prescription of black hole growth described in equation (1) to reproduce the observed $M_{\rm BH}-M_{\rm Bulge}$, especially at high masses, has already been discussed in previous works (Croton et al. 2006; Marulli et al. 2008) (here the scatter is larger than previously shown as we include in the figure also satellite galaxies). For the growth of massive seeds soon after formation, we do not impose any preferred scaling with the mass of the host galaxy or DM halo, but rather a very simple self-regulation mechanism, where the main unconstrained parameter is the size of the reservoir cloud from which the new massive seeds can grow (see equation 4). In Fig. 10, the red dots indicate where massive seed descendants sit in the relation, for a 1 pc reservoir (upper panels) and a 0.1 pc reservoir (lower panels), with the symbols colour-coded depending on the redshift of the formation of the seed. The oldest black holes from direct collapse formed around $z = 12$, and they are among the most massive black holes at $z = 0$, but there is also a large number of black holes that formed at later times and quickly accreted to the highest masses. In the 1 pc reservoir case, as soon as they are formed, the seeds sit on the relation, or slightly above it. It is interesting that the simple self-regulation mechanism for newly formed massive seeds is able to bring them close to the relation, when $r_{\rm r} = 1$ pc is assumed. During subsequent mergers, the black holes from massive seeds grow along the $M_{\rm BH}-M_{\rm Bulge}$ following the prescription for light seeds (equation 1), and, by $z = 0$, the most massive black holes show very little scatter. The picture is different when a 0.1 pc reservoir cloud is assumed: the seeds are allowed to grow to higher masses during the first phase of accretion, and only the black holes that experience many subsequent mergers head towards the relation. At $z = 0$, the most recently formed massive seeds are well above the relation. Assuming that the value of $r_{\rm r}$ would be in between the two values adopted here, our model predicts outliers in the relation. Detecting such outliers might be observationally difficult, given the challenges in measuring directly black hole masses and given the low space density of black hole descendant of massive seeds. However, recent observations have detected massive black holes well above the mean scaling relation (e.g. McConnell et al. 2011; van den Bosch et al. 2012). In particular, van den Bosch et al. (2012) estimated the mass of the central black hole in the compact lenticular galaxy NGC 1277 to be 59 per cent the mass of the bulge. The galaxy is characterized by a very old ($\gtrsim$8 Gyr) stellar population, suggesting that most of black hole accretion likely occurred at early epochs. Whether the black hole hosted by NGC 1277 could be a massive seed remnant is an interesting possibility. Not only our model predicts that the descendants of massive seeds can be outliers in the scaling relations with the galaxy, but we also note that galaxies hosting a black hole from a massive seed tend to have had a last major merger earlier than galaxies hosting an equally massive black hole descendant of a light seed (see the bottom-right panel of Fig. 9). The different merger histories imply that the galaxies hosting massive seeds are likely characterized by older stellar populations, as the one of NGC 1277.

3.3.3 *Properties of the host galaxies and haloes*

In Fig. 11, we show the morphological properties of the galaxies hosting descendants of light and massive seeds. The top panels show the distribution in bulge-to-total ratio of the galaxies hosting black holes with light seed (top-left) and massive seed (top-right) progenitor as a function of the black hole mass at $z = 0$. For the descendants of light seeds, small black holes live predominantly in disc-dominated galaxies (blue area), while the majority of massive black holes sit in bulge-dominated galaxies (red area). For massive seed descendants, the morphology distribution of host galaxies is more constant across the black hole mass, with an essentially negligible number of black holes in purely disc galaxies. In the lower panels, the same morphology distribution of host galaxies is shown for objects at $z = 2.5$ and, in this case, only galaxies hosting an actively growing black hole (accreting at a rate higher than 10 per cent of Eddington) are included in the calculation. At this redshift, very few black holes above 10^9 M$_\odot$ are active (see the active mass function, shown by the dashed curves in Fig. 5), so we exclude them from the present calculation. Black holes from light seeds sit mainly in disc-dominated galaxies, and only a negligible number are in spheroids. The same holds for the active descendants of massive seeds in the 10^7–10^8 M$_\odot$ range, but the smaller black holes (mainly recently formed seeds) are essentially only hosted by ellipticals.

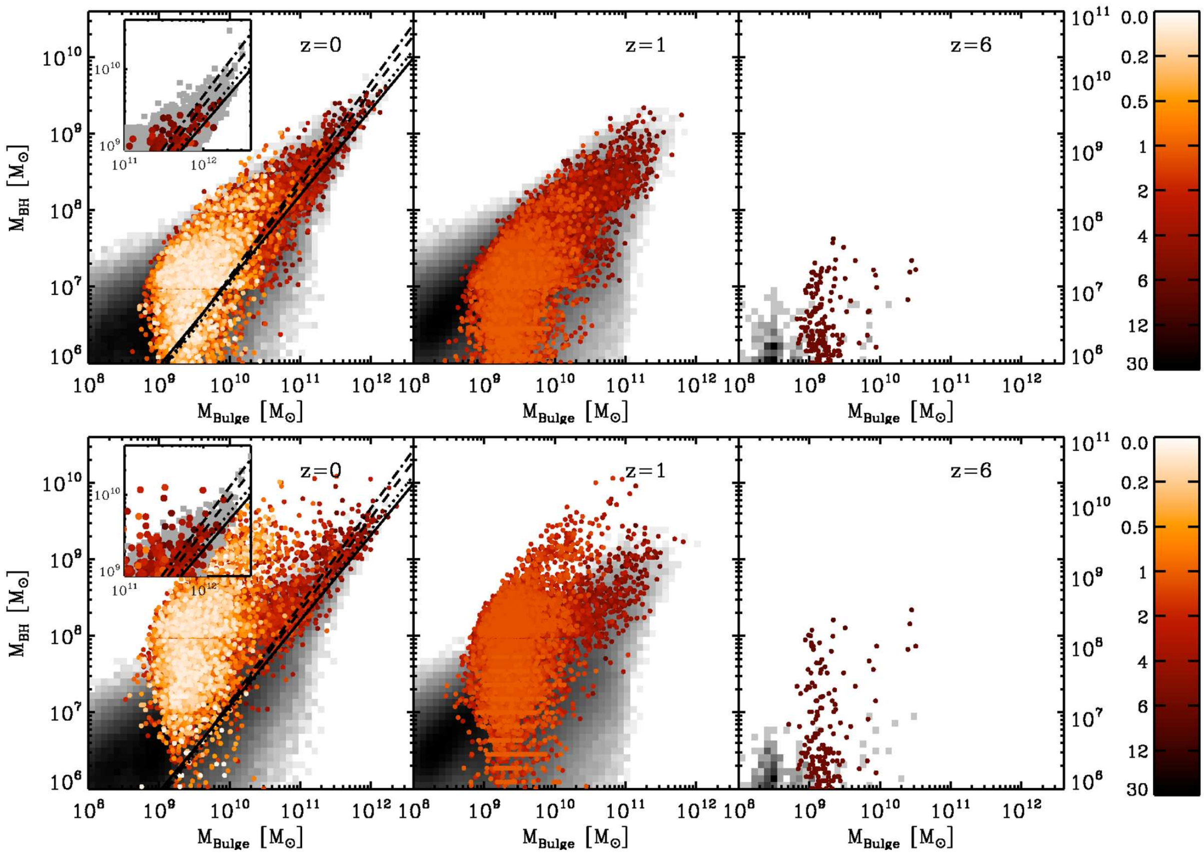

Figure 10. Relation between the black hole mass and the bulge mass at three different redshifts, as indicated in the panels. The grey area indicates the relation for light seed descendants. The red points indicate the position on the relation for the black hole descendant of massive seeds. Darker red corresponds to higher formation redshift, as indicated in the side colour bar. In the top panel, the massive seeds formed assuming a radius of 1 pc for the nuclear gas reservoir, whereas in the bottom panel the reservoir has been assumed to have a radius of 0.1 pc. The solid lines at $z = 0$ show some fit from observational data (Häring & Rix 2004; Gültekin et al. 2009; Hu 2009).

Our model clearly predicts quite different morphological properties for the galaxies hosting light and massive seed remnants, in particular for black holes of intermediate small mass scales. Galaxy morphology could then contain important information on the origin of the hosted black holes.

We now look at the properties of the DM haloes hosting massive seeds. In the left-hand panel of Fig. 12, we show, at various redshifts, the mass function of the haloes (solid lines) and subhaloes (dotted lines) hosting newly formed massive seeds (for central galaxies we take the virial mass of the halo as the subhalo mass). The mass functions clearly peak at $10^{11}\,\mathrm{M}_{\odot}$, as expected, given that we impose that value as the minimum halo mass where massive seeds can form. As in central galaxies, according to our definition, the subhalo and halo masses are equivalent, the two mass functions trace each other for massive seeds forming in central galaxies. This seems to generally be the case for massive seeds forming in haloes smaller than $\sim 10^{12}\,\mathrm{M}_{\odot}$. At larger masses, while the subhalo mass function drops quickly, the halo mass function flattens out and, at lower redshifts, reaches very high masses: these are massive seeds forming in subhaloes that are the hosts of satellite galaxies in larger haloes, which reach the masses typical of clusters. We find, in fact, that at $z = 0$ about 20 per cent of newborn massive seeds are in satellite galaxies.

In the right-hand panel, we show in which haloes the descendants of these massive seeds are today: seeds formed at very high redshifts sit in very massive haloes, with only a small fraction in haloes below $10^{12}\,\mathrm{M}_{\odot}$. The descendants of seeds forming at more recent times are also sitting in massive clusters, but there is still a fraction of the population in smaller haloes.

3.3.4 Clustering

It is well known that the space distribution of DM haloes and galaxies can be different from the distribution of the underlying DM (Kaiser 1984; Bardeen et al. 1986). The two-point autocorrelation function[7] provides information on how strongly a given class of objects is clustered at a given scale, and from the amplitude and shape of this function it is possible to extract important information on the environment of the objects analysed.

One of the main advantages of studying galaxy evolution in models run on DM simulations rather than extended Press–Schechter models is the possibility of studying the clustering of a targeted set of objects, using the distribution of the DM haloes in which the objects reside.

[7] The *two-point spatial autocorrelation function* $\xi(r)$ for a given class of objects is defined as the excess probability for finding a pair at a distance r, in the volume elements $\mathrm{d}V_1$ and $\mathrm{d}V_2$: $\mathrm{d}P = n^2[1 + \xi(r)]\mathrm{d}V_1\mathrm{d}V_2$, where n is the average number density of the set of objects under consideration (e.g. Peebles 1980).

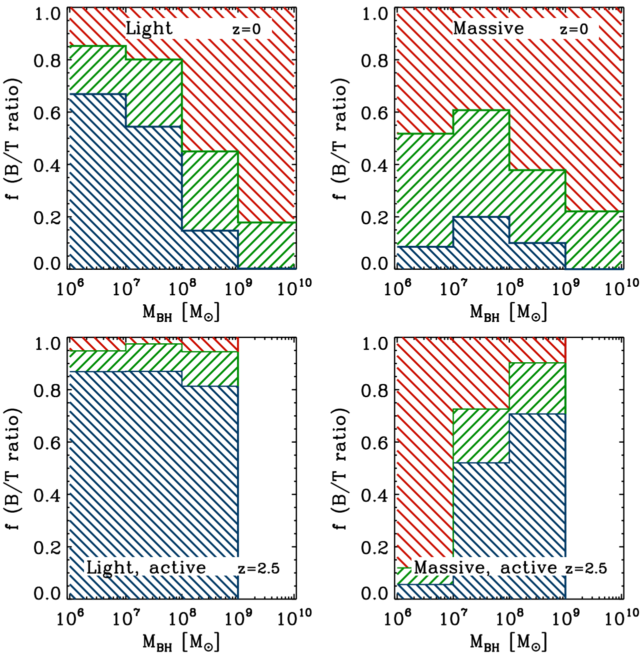

Figure 11. Morphological distribution of the galaxies hosting the descendants of light or massive seeds (left- and right-hand panels, respectively), at $z = 0$ (upper panels) and at $z = 2.5$ (lower panels). At each black hole mass, the area of different colours indicates the relative contribution of galaxies with different morphologies, defined through the bulge-to-total ratio: blue refers to discs or extreme late-type ($B/T < 0.3$), green to normal spirals ($0.3 < B/T < 0.7$) and red to elliptical galaxies ($B/T > 0.7$). At $z = 2.5$, only active black holes are considered.

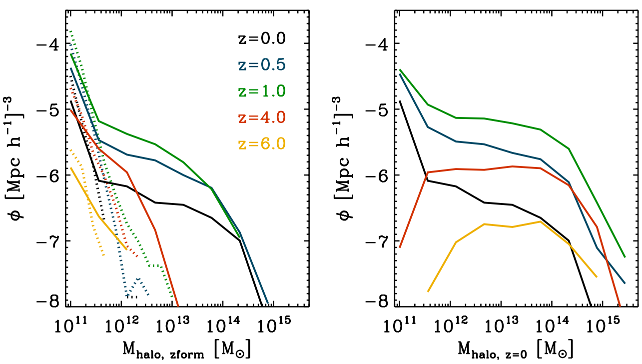

Figure 12. Left-hand panel: at various redshifts, the mass function of the DM subhaloes (dotted lines) and haloes (solid lines) hosting newly formed massive seeds. Right-hand panel: local mass function of the haloes hosting the descendants of the massive seeds formed at the redshifts of the left-hand panel.

At any given time, the most massive DM haloes are the most rare and biased[8] objects, corresponding to the highest peak of the DM density field. While the clustering amplitude of DM haloes depends mainly on halo mass and only weakly on other properties, such as assembly history, concentration and recent mergers (e.g. Gao, Springel & White 2005; Wechsler et al. 2006; Angulo, Baugh & Lacey 2008; Bonoli et al. 2010), the clustering of galaxies depends strongly not only on mass, but also on galaxy properties such as colour and surface density: for example, at fixed stellar mass, red and passive galaxies cluster more strongly than blue, star-forming galaxies (e.g. Li et al. 2006), which is a consequence of galaxies of a given stellar mass, populating different DM haloes.

Here we want to study the clustering properties of galaxies that host the recent formation of a massive black hole seed, to further gain insights into the large-scale environment of these events. In Fig. 13, we show the $z = 0$ two-point correlation function of galaxies that experienced a major merger that led to the formation of a massive seed (red solid curves). For comparison, we also show the two-point correlation function of all other major mergers at the same epoch that did not satisfy the conditions for direct collapse (blue dashed curves), randomly extracting, from the entire population, a subsample that matches the massive seed population in a number of objects and in the distribution of stellar mass (left-hand panel), black hole mass (central panel) or halo mass (right-hand panel). Using the same matching criteria, we also randomly extract subsamples from the entire galaxy population, and the correlation function of these objects is indicated by the green dot–dashed lines. To calculate the uncertainty in the autocorrelations due to random sampling, for each matching criterion, we selected 100 random subsamples from the parent populations, and the error bars bracket the 10 and 90 percentiles of the distribution. We find that galaxies that recently experienced a direct collapse event are significantly less clustered than the rest of the major-merger population and the entire galaxy population, when these are matched by stellar mass or black hole mass (left and central panels). Moreover, all recent mergers (both the ones that lead to a massive seed and the ones that preserve the small seed) are antibiased with respect to the DM distribution. In contrast, the random samples extracted from the entire galaxy population are slightly biased. Clearly, this indicates that galaxies with similar stellar mass or black hole mass cluster differently depending on whether they experienced a recent major merger. This is in line with the observational results indicating that blue active galaxies are less clustered than red passive ones. When matching samples by halo mass, these differences essentially vanish. We find, in fact, that, at fixed stellar mass, galaxies with a recently formed massive seed tend to be found in less massive haloes than the average galaxy and, when we match out samples by halo mass, the differences in clustering get erased as halo clustering depends primarily on mass. The smaller clustering amplitude of recent mergers (and, to an even larger extent, of mergers that lead to direct collapse) indicates that, in the local universe, antibiased galaxies are the possible sites for finding on-going events of direct collapse. We find that these are mainly galaxies that lived in isolation for most of their lives, and that only recently experience encounters with other objects with similar properties.

We also looked at the clustering behaviour of galaxies hosting newly formed massive seeds at high redshift, but we could not find a signal as strong as the one showed above: all samples show a similar clustering amplitude, independently of the assumed matching property. Unlike the $z = 0$ results, we also find that at high redshifts galaxies hosting a new massive seed show a much higher correlation function than the underlining DM distribution, which is expected, given that haloes above $10^{11}\,M_\odot$ (which is the imposed minimum mass in which massive seeds can form) reside in higher and higher density peaks as redshift increases. This is in line with quasar measurements at high redshifts ($z > 2$), which indicate that bright quasars are a highly biased population, living in high-density peak (e.g. Shen et al. 2007, 2009). In our model, the black hole descendants of massive seeds dominate the massive end of the mass function at very high redshift (see Fig. 5), so

[8] At any given scale, the bias parameter indicates how more (or less) clustered objects are with respect to the DM.

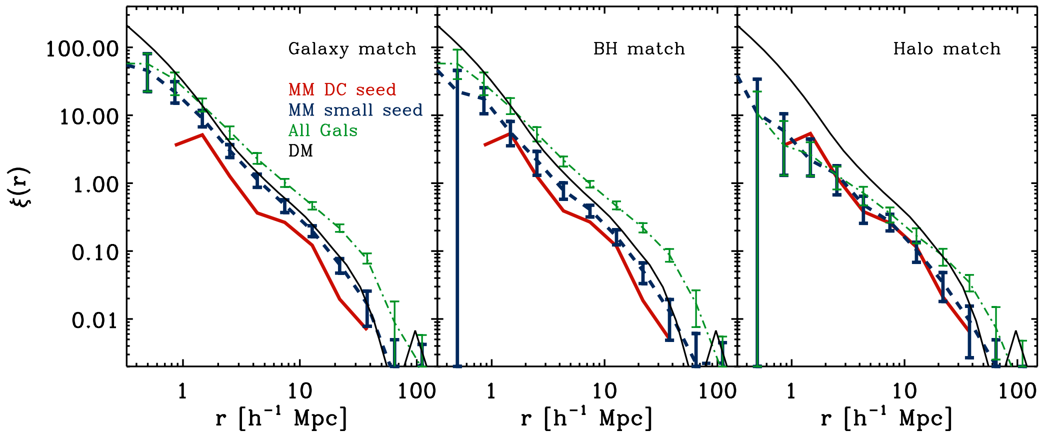

Figure 13. Two-point autocorrelation function of galaxies hosting the formation of massive black hole seeds from major mergers (red curves) at $z = 0$. The blue dashed curves and the green dot–dashed curves show the correlation function of, respectively, other major mergers and the whole galaxy population with matching stellar mass (left-hand panels), black hole mass (central panels) and dark halo mass (right-hand panels). The solid line indicated the autocorrelation of the DM in the Millennium Simulation.

these could be the objects powering the brightest highly clustered quasars.

4 SUMMARY AND CONCLUSIONS

In this paper, we have introduced a new scenario for the formation of massive black hole seeds. Based on the results of the set of hydrosimulations from M10, we tightly link the formation of a massive black hole to the major mergers of gas-rich disc-dominated massive galaxies with no pre-existing massive black hole at their centre. Such mergers can, in fact, easily channel a lot of gas at the centre of the merger remnants, forming a sub-parsec-scale cloud which will likely lead to a massive black hole seed either through direct gravitational collapse or, more likely, through a supermassive star/quasi-star phase. In mergers of this kind, in fact, the accretion rates to the centre are seen to be orders of magnitude higher than in isolated protogalaxies.

We developed a formalism to track such events in galaxy formation models to predict the evolution and environment of massive seeds across cosmic time. Rather than tuning the model-free parameters that control the formation of massive seeds with observational data, we set their value using the findings of the hydrosimulations of M10, so that all our results on massive seeds can be considered genuine predictions of theoretical models. Our main results are as follows.

(i) At redshifts above $z \sim 3$–4, almost all major mergers of galaxies residing in haloes of at least $10^{11}\,\mathrm{M}_{\odot}$ meet the imposed conditions for the formation of a massive black hole seed. At lower redshifts, the fraction of major mergers able to produce a massive seed strongly drops, and, by $z = 0$, the fraction has reduced to ∼20 per cent. This dropping is due to the sharp decrease in the probability of having a major merger which involves two disc galaxies with a still small black hole.

(ii) Massive black hole seeds can dominate the massive end of the mass function above $z \sim 1$ or $z \sim 3$ depending on the radius of the gas reservoir from which they accrete just after their formation. Newly formed massive seeds are, in fact, allowed to accrete from the surrounding gas until their feedback energy is able to unbind it. As the binding energy of the gas reservoir depends on its physical size (at fixed mass), massive seeds grow to larger masses in the model runs where the reservoirs are assumed to be smaller.

(iii) The total black hole mass density evolution up to $z \sim 3$ well matches observational estimates using the Soltan argument (Soltan 1982). At higher redshift, the mass density is dominated by the massive seed remnants, and its evolution depends on the specific assumption for massive seed formation, with a smaller reservoir cloud (or smaller feedback coupling) leading to higher mass densities at high redshifts.

(iv) Massive black hole seeds soon after formation sit close or above the $M_{\mathrm{BH}}-M_{\mathrm{Bulge}}$ relation, depending mainly on the size of the reservoir assumed. We generally expect a fraction of descendants of massive seeds to still be above the relation in the local Universe.

(v) Massive seeds evolve very rapidly at high redshift, but do not grow significantly in the local universe. Of the most massive black holes today, the ones descending from a massive seed sit, in fact, in galaxies that had a first major merger very early. In contrast, the massive descendants of light seeds are in galaxies that had a first major merger relatively recently, but grew very quickly to high masses.

(vi) While the most massive black holes today sit in bulge-dominated galaxies, independently of whether they descend from a light or massive seed, the morphology of the host galaxies of smaller black holes is very different for the descendants of light and massive seeds: black holes between 10^6 and $10^8\,\mathrm{M}_{\odot}$ with a light seed progenitor preferentially sit in disc-dominated galaxies while the descendants of massive seeds in the same mass range are hosted by bulge-dominated galaxies.

(vii) Galaxies that host massive seeds formed at very recent times have significantly lower clustering amplitude than a random subsample of the global galaxy population with the same stellar mass distribution. While this can be explained by the fact that, at fixed stellar mass, recent mergers take place in smaller haloes, the observational signature of this effect should be very clear.

Massive black hole seeds are a very attractive scenario alternative or, more likely, complementary, to models of light seeds from Pop III stars or the collapse of nuclear star clusters. While massive seeds from metal-free protogalaxies can only form at very high redshift, in this work we have shown that massive seeds from galaxy mergers, which do not require metal-free gas but rely on a different set of conditions, can form both at high redshift and at more recent times. While we have considered a purely hydrodynamical formation scenario for the massive seeds, which, at small scales, would be compatible with the quasi-star model of Begelman and collaborators, the results of our model should hold even if the ultimate collapse into a seed would take place in a different way, such as involving the core collapse of a massive nuclear cluster of normal stars (Davies, Miller & Bellovary 2011), as long as the formation of the precursor supermassive gas cloud occurs under the conditions that we have considered here. Whether the 'birth' of such black holes could be observed directly is still very uncertain. A promising detection channel has recently been suggested by Czerny et al. (2012), who claim that quasi-stars might emit jets whose gamma-ray emission might account for the unidentified gamma-ray sources. The quasi-star phase, which has an emitted spectrum very similar to that of a red giant star, might be detectable with the James Webb Space Telescope at high redshift given the relative high frequency of seed formation events expected in models that rely on the merger rate of galaxies such as in our scenario or in other recent direct collapse models (Volonteri & Begelman 2010). On the other hand, seed formation events occurring at low redshift might be eventually identified by exploiting the information presented in this paper on the environment and nature of their host galaxies. Indeed, those events should take place in underdense regions, perhaps in voids or at least field-like environments, where gas-rich, massive disc-dominated spirals are common (good examples of such galaxies are indeed those in the local 8 Mpc volume; e.g. Kormendy et al. 2010). The differences in clustering amplitudes of host galaxies might also be an interesting route to test our scenario We will dedicate a follow-up paper to a detailed and quantitative analysis to possible strategies to detect individual events or the global population of massive seed remnants at both high and low redshifts.

ACKNOWLEDGEMENTS

We thank Marta Volonteri, Mitch Begelmann, Takamitsu Tanaka, Raul Angulo and Simon White for useful discussions and comments on the manuscript. SB particularly thanks Simon White also for the generous hospitality at the Max Plank Institute for Astrophysics, where a large fraction of this work has been carried on. Finally, we thank the anonymous referee for the many suggestions that improved the quality of the paper.

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